Bently's Corner

Vibration analysis techniques for detecting and diagnosing shaft cracks

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President and Chairman

Because other malfunctions can cause a machine to exhibit similar symptoms as those experienced under a shaft crack condition, it's important that the proper diagnostic methods are used to diagnose a shaft crack.

There are two fundamental symptoms of a shaft crack at operating speed:

1) Unexplained changes in the synchronous speed (1X) shaft relative amplitude and phase and/or slow roll bow vector, and

2) The occurrence of twice rotative speed (2X) vibration, which may or may not occur at operating speed.

Changes in (1X) rotative speed behavior

The vital and primary symptoms of a shaft crack are changes in the synchronous (1X) amplitude and phase and/or slow roll bow vector. Changes in the synchronous (1X) amplitude and phase, which have been observed at operating speed on large turbine generators with shaft cracks, is the most important indicator of a shaft crack.

Shaft measurements are the only effective method for measuring changes in the synchronous (1X) amplitude and phase and the slow roll vector. While housing measurements may be helpful, they cannot measure the slow roll vector and low-speed vibrations of the shaft.

The changes in synchronous (1X) amplitude and phase are caused by the shaft bowing due to an asymmetric transverse crack (Figure 1). This causes a modification of the slow roll readings as the bowed shaft generates an additional unbalance.

In this situation, the synchronous (1X) amplitude and phase changes—either higher or lower. In all observed cases where the crack has grown larger than 50 percent through the shaft, however, the (1X) rotative speed amplitude component has grown *larger* in the final stages.

Occurrence of 2X component

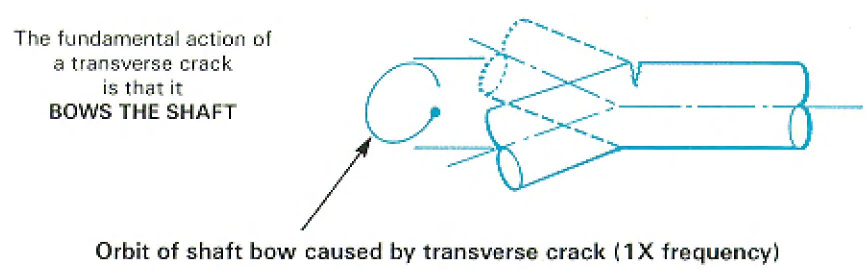
The secondary, and classical, symptom—the occurrence of the 2X component—is caused by asymmetry of the shaft. The 2X component is due to a combination of a transverse crack—which causes shaft asymmetry—and a steady-state radial load. On horizontal rotors, the radial load can be caused by gravity. On vertical machines, the radial load can be generated by misalignment or fluid flow.

The 2X frequency component is especially dominant when the rotative speed is in the region of half of any rotor system natural frequency. Figure 2 shows a spectrum cascade plot and the corresponding orbits, which identify this classical shaft crack behavior as well as the bow/nonlinear response.

Monitoring changes in 1X component at operating speed

The change in synchronous (1X) amplitude and phase, measured by shaft relative probes, can be monitored under normal operating conditions to provide alarming and early warning of a shaft crack.

The polar plot provides an excellent format for documenting the shift in synchronous (1X) amplitude and phase. The shift is monitored at slow roll and under the normal range of operating conditions while at operating speed.



This causes: (1) Changing 1X (synchronous) vibration behavior at speed and load.
(2) Erratic response to attempted balancing.
(3) Changes in the slow roll bow vector (at low rotative speeds).

Further, as the bow increases, a totally different type of 2X behavior may occur. (See spectrum cascade of cracked shaft).

Figure 1

A normal operating range of the 1X vibration vector is determined within the plot to form what is called an "acceptance region." The actual 1X vibration vector is then plotted.

Deviation of the 1X vibration vector from the acceptance region can be a vital warning of a shaft crack, even though many other rotor disturbances can also cause some deviation from the acceptance region (Figure 3). Similar techniques can be used to monitor changes in the slow roll bow vector.

Changes in synchronous (1X) amplitude and phase must be analyzed in conjunction with other vibration information—including the twice rotative speed (2X) machine behavior—to determine whether the shifts were caused by an asymmetric transverse crack or other factors. The other factors can include load, field current, steam conditions, thermal expansion, or other operating parameters.

Monitoring 2X behavior on startup and shutdown

On startup and shutdown, two types of plots for the twice rotative speed (2X) component of the shaft dynamic motion can be plotted for both the vertical and horizontal shaft-observing probes:

1) 2X polar plot, and

2) Spectrum cascade plot that documents the 2X behavior from slow roll to operating speed.

When there is shaft asymmetry, the polar loop will occur at each balance resonance of the machine. Take a 3,600 rpm machine with its first balance resonance at 1,600 rpm, for example.

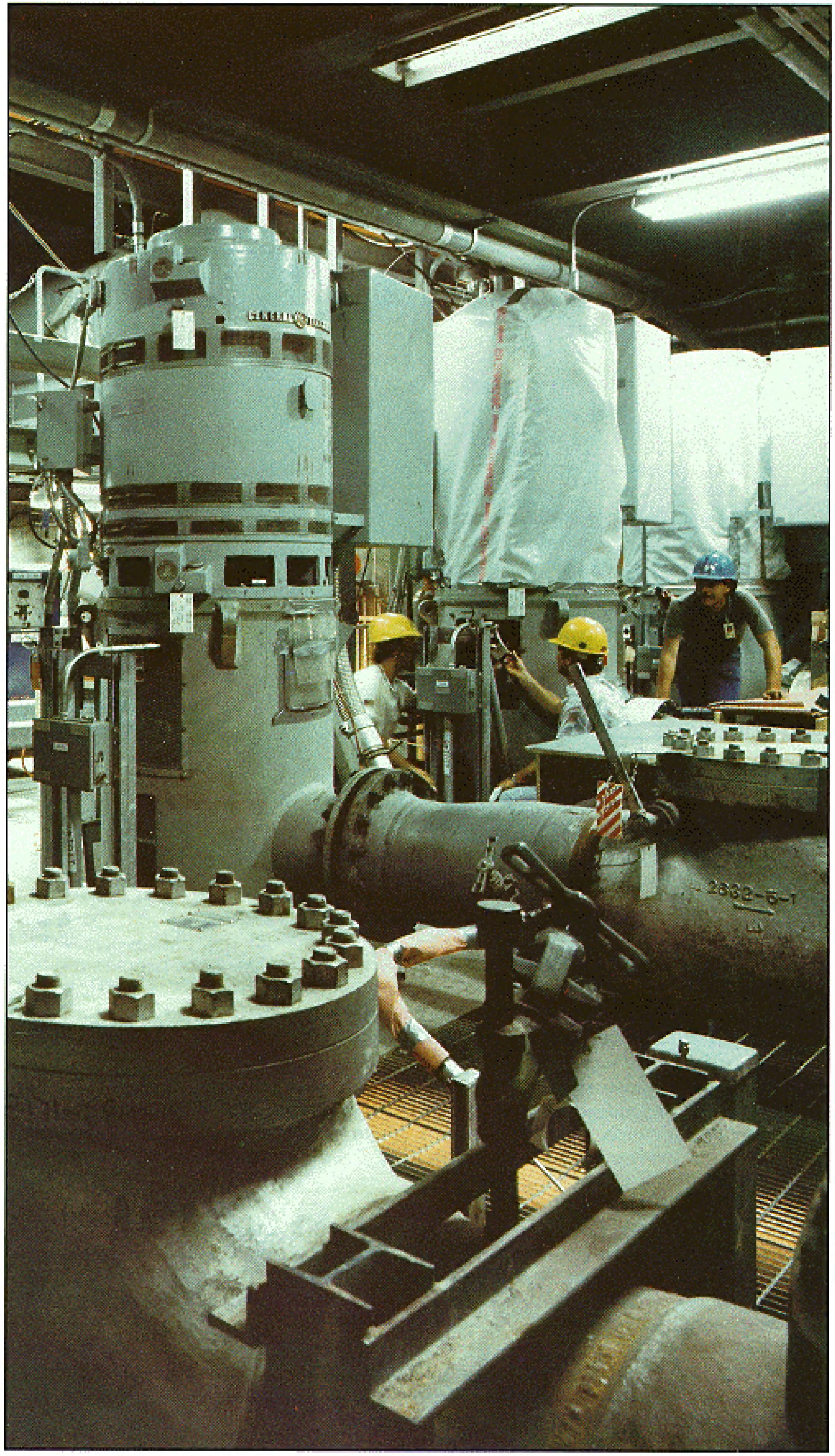
When the rotative speed is in the range of 800 rpm, the first polar loop will occur. If the second pivotal resonance is at 6,800 rpm, the second 2X polar loop will be at its maximum in the range of 3,400 rpm.

The high 2X vibrations can be observed on a spectrum cascade plot as bumps on the 2X line at corresponding rotative speeds.

As a result of recent laboratory research and field experience, it is believed that 2 mils peak-to-peak of 2X component is the mandatory shutdown level for a shaft crack. For a given percentage of transverse cracks, this level may vary, depending upon:

1) the crack location relative to the mode shape of that resonance,

2) the rotor system damping for that ►



The vibration analysis techniques for detecting and diagnosing shaft cracks can be used on vertical pumps and other types of rotating machinery.

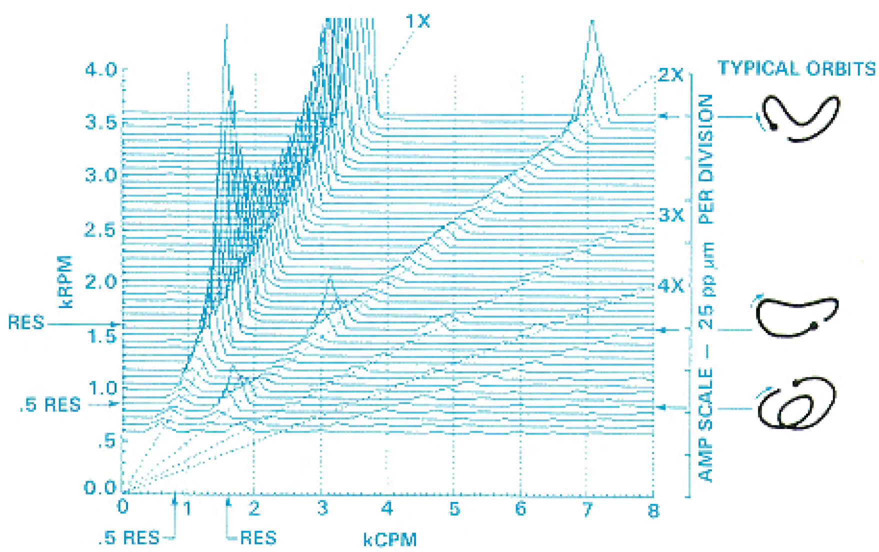
resonance (although the damping is usually constant for most turbine generators),

3) the amount of static preload (if there is zero static preload, the 2X component would also be zero), and

4) the probe location along the shaft.

It is normal for a generator—especially a two-pole generator—to have some asymmetry and, therefore, a normal residual 2X reaction. Preliminary results of a review of many generators' behavior has shown that this asymmetry produces a 2X reaction well below 1 mil peak-to-peak.

While it is normal for the horizontal 2X motion of the shaft to be slightly higher than the vertical 2X motion when the preload is gravity, it is our belief that both the vertical and horizontal 2X motion should be observed using proximity probes. In at least one documented save on a turbine generator, only vertical probes had been installed. The shaft crack could have been detected earlier using horizontal as well as vertical probes.



SPECTRUM CASCADE OF CRACKED SHAFT

The above spectrum cascade plot shows the vibration response (amplitudes and frequencies) from a proximity displacement transducer at different speeds during a shutdown of a rotor with a cracked shaft. Two types of 2X components caused by a cracked shaft can be observed in this example.

When the rotative speed (800 rpm) is at half the resonance speed (1600 rpm), the 2X frequency component has its resonance. The orbit shows the typical inside loop. This 2X motion is driven by a preload (like gravity) and shaft nonsymmetry due to a crack. The 2X component is present even though the 1X component is small.

When the shaft bow gets large as the rotative speed approaches the resonance speed a steady state preload causes the rotor reaction shown by the orbit at 1600 rpm. Notice that the 2X, 3X, and 4X harmonics are also incurred. This 2X motion is driven by the 1X and therefore, is only present when large 1X orbiting occurs.

At 3600 rpm a large 1X vibration again occurs (second resonance). In conjunction with the preload, it causes the resulting 2X frequency component. The corresponding orbit is shown.

Figure 2

Using 2X information in machine save

Even though the 2X component does not necessarily appear at operating speed, a recent shaft crack save exhibited this classical phenomenon. In this case, the plant engineers and manufacturer's engineer observed and acted upon the following information on a vertical pump used in nuclear power plant service to accomplish an excellent save:

1. Increasing overall vibration levels.
2. Large 1X and 2X frequency vibrations.
3. 2X frequency vibration that remained at the same level after the machine was trim balanced. The 1X frequency vibration was significantly decreased by trim balancing.

The engineers used the vibration information to determine whether the machine response was caused by other possible malfunctions, such as unbalance, misalignment, etc. After eliminating the other possible malfunctions, the engineers determined there was a high probability of a shaft crack.

The machine was taken out of service and inspected. Inspection confirmed their diagnosis.

Analyzing orbit patterns

Observation of orbits is also useful for revealing a shaft crack. Figure 4 shows the typical orbit patterns for a shaft with a large 1X and 2X components.

The orbit patterns show that the rotor moves toward the direction of the preload twice during each shaft rotation. This results in a 2X component. Future changes in the orbit pattern are dependent on the phase angle relationship between the 1X and 2X components.

When these orbit patterns are detected, other machine malfunctions must be eliminated to determine whether a shaft crack is the root cause of the problem. A large 1X component can be caused by a shaft thermal bow as well as a shaft crack. A preload, due to misalignment, as well as a shaft crack can cause an increase in the 1X and 2X components.

When the thermal bow is removed, the 1X and 2X components disappear. When only the steady-state load is removed, the orbit becomes a 1X circle, or ellipse, without a 2X component. The two separate methods of 2X formation may occur together when both situations are present (see Figures 2 and 4).

Mode identification probes for observing machine behavior

To obtain vibration information for detecting shaft cracks, mode identification XY proximity probes—located at various longitudinal positions along the rotor to observe the shaft—and a Keyphasor reference are required.

These probes make it possible to reliably observe the significant indicators of a shaft crack—the action of the shaft vibration patterns at operating speed and bow changes at low rotative speeds. They also make it possible to identify nodal point regions and rotor mode shapes at various rotative speeds.

The mode identification XY proximity probes should be used to continuously monitor machines that are susceptible to shaft cracking. The use of these probes also overcomes the potential danger—when only a single set of XY proximity probes is used—of locating the probes at a nodal point along the rotor.

What to do when your machine experiences any of the shaft crack symptoms

As stated before, because other malfunctions can cause the machine to exhibit similar symptoms as those experienced under a shaft crack condition, the proper methodology must be used to diagnose a shaft crack.

Two recent shaft crack saves illustrate this point. The engineers originally suspected imbalance as the cause of the problem, but the machine did not respond properly to several balancing attempts.

Difficulty in trim balancing often is a warning sign of a cracked shaft. Further analysis of the symptoms is required to determine the root cause of the problem.

The following procedures are recommended to avoid missing the symptoms of a shaft crack when trim balancing:

1) Employ only modern calibration weight balancing methods.

2) Tape record the startup and shutdown of each balance run.

3) Allow no more than two or three balancing attempts.

4) Allow the balancing weights to generate the centrifugal force by being no more than 50 percent of the weight of the rotor.

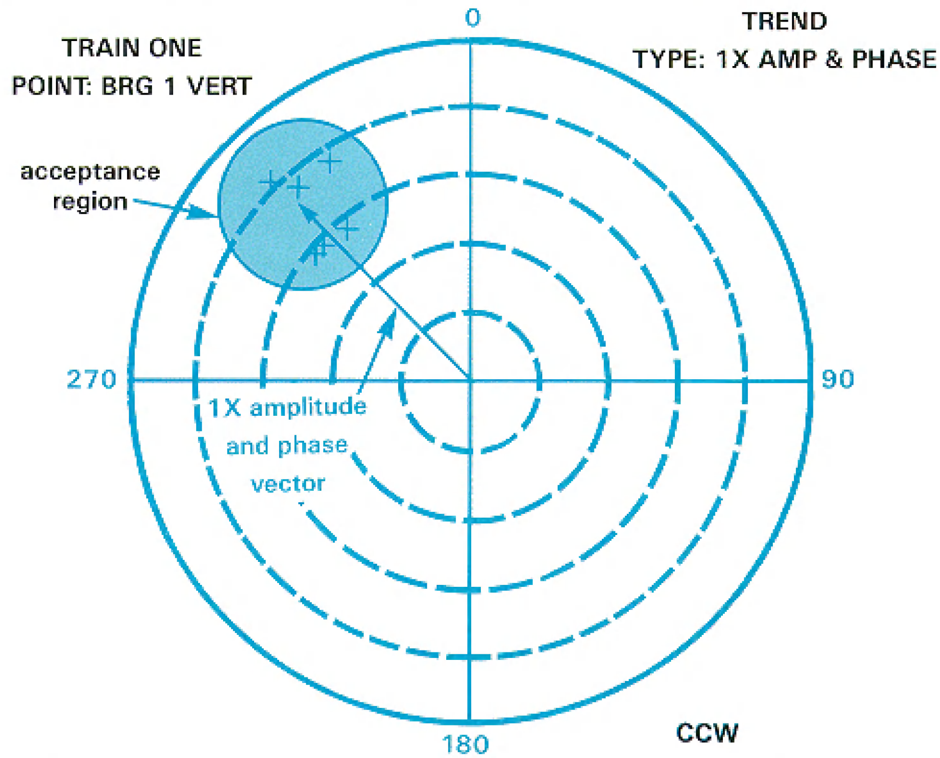
5) Be extremely cautious when the trim weights are applied opposite of the location of previous weights. This is another indicator of a shaft crack.

6) Immediately reduce the startup and shutdown data in spectrum cascade plots and 1X and 2X polar plots. Study these plots for indications of a shaft crack.

Bently Nevada's Mechanical Engineering Services (MES) engineers are trained to perform machine analysis, including diagnosing shaft cracks and other malfunctions. They also are trained to perform balancing—using modern techniques—and to document the response vectors during the balancing process for the user's records.

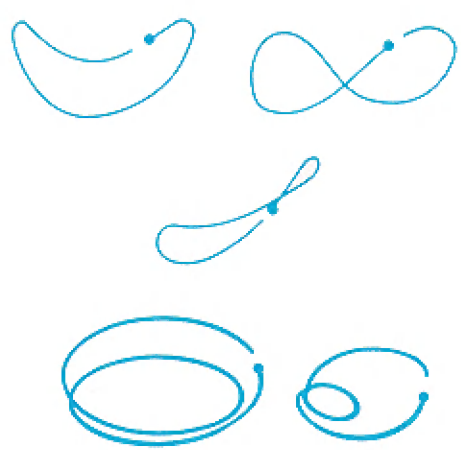
For a brochure on MES' services, please check L0507 on the return card.

For an application note on the use of mode identification probes, please check L0638 on the return card. ■



The polar plot is a presentation of vector monitoring. The 1X (or 2X) amplitude and phase vector is monitored to ensure it remains within an acceptance region. When the vector moves outside the acceptance region, further diagnostics are necessary. This is especially important for monitoring for cracked shafts.

Figure 3



Examples of orbits of a rotor with a cracked shaft and resulting shaft bow combined with a steady-state preload, such as gravity.

Examples of orbits of a rotor with a cracked shaft where the 2X frequency component results primarily from a preload, like gravity. These are the classical 1X and 2X orbits for a cracked shaft, at a half first balance resonance speed.

Figure 4